Effect of Lubricant Film Thickness on Bearing Life under Contaminated Lubrication
Part 2: Relationship between Film Thickness and Dent Formation

T. SADA  T. MIKAMI

To date, lubricant film condition represented by film parameter has been disregarded for the most part in studies of debris-induced failure of rolling bearings. However, as discussed in Part 1, film condition is a principal factor in not only bearing life but also failure mode under severe contaminated lubrication. In the life tests described in Part 1, many dents were formed on the raceways and bearing life was reduced with increasing lubricant film thickness. These results indicate that the degree of denting affects bearing life, and the film condition is closely related to dent formation. In this paper, the relationship between film condition and dent formation is investigated, and the mechanism of difference in degree of denting with change in film thickness is discussed.

Key Words: rolling bearing, fatigue life, contamination, lubricant film thickness, debris dent

1. Introduction

In Part 1, life tests for ball bearings were carried out in lubricating oil that contained solid debris. It was found from the results that lubricant film condition between the rolling element and the raceway is an important factor dominating the life and the failure mode of rolling bearings under contaminated lubrication. To date, several studies have been conducted to investigate the behavior of debris particles in elasto-hydrodynamic lubrication (EHL) contact by experimental observations or numerical simulations. From these results, new knowledge about the effects of debris features, their concentrations and the relative speed of contact surfaces on the degree of denting has been obtained. However, in these studies, the effect of film condition in EHL contacts on dent formation has not been discussed.

In this paper, the relationship between lubricant film thickness and dent formation is clarified by measuring the area densities of dents formed on the inner raceways of test bearings after the life tests described in Part 1. In addition, the process of dent formation is discussed by measuring the changes in dent area density during life tests.

2. Life Test Results Discussed in Part 1

The life test results discussed in Part 1 are summarized in Table 1. Two kinds of life test were carried out using 6206 deep groove ball bearings as test bearings. In the first test, the same oil was used for various loading conditions (series A). In the second test, lubricant film thickness was kept constant by using different viscosity oils for each loading condition (series B). Every test was performed with inner ring rotation in an oil bath that contained particles of high-speed tool steel as debris. Hardness of the particles was 800 HV. Size of the particles ranged from 100 to 150 µm in diameter.

Table 1 Life test results discussed in Part 1

<table>
<thead>
<tr>
<th>Test name</th>
<th>Load, N</th>
<th>Lubricating oil</th>
<th>Central film thickness $h$, µm</th>
<th>$L_{10}$ life, h</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>686</td>
<td>VG68</td>
<td>0.227</td>
<td>386.85</td>
</tr>
<tr>
<td>A-2</td>
<td>3 430</td>
<td></td>
<td>0.153</td>
<td>49.10</td>
</tr>
<tr>
<td>A-3</td>
<td>6 860</td>
<td></td>
<td>0.107</td>
<td>7.97</td>
</tr>
<tr>
<td>B-2</td>
<td>3 430</td>
<td>VG220</td>
<td>0.239</td>
<td>14.24</td>
</tr>
<tr>
<td>B-3</td>
<td>6 860</td>
<td>VG320</td>
<td>0.219</td>
<td>4.64</td>
</tr>
</tbody>
</table>

The relationship between load and $L_{10}$ life obtained through the life tests is shown in Fig. 1. In test series A, using the same oil for various loading conditions, the degree of change in life with variation in load tended to become smaller as the load decreased, whereas in test series B, performed under constant film thickness, the
load-life relation was constant. In addition, under the same load, the bearing life in test series B, with large film thickness, is shorter than that in test series A.

Appearance of the inner raceways after the life tests indicated a tendency for a large number of debris dents to be formed under large film thickness condition in which the life reduction from the basic rating life was remarkable. This circumstance indicates that the degree of denting affects bearing life and the degree of denting is correlated with the lubricant film condition. The effect of film condition on dent formation is discussed in detail below.

3. Measurements of Dent Area Density

First, to investigate the relationship between lubricant film condition and degree of denting under contaminated lubrication, the dent area densities were measured on the inner raceways of ball bearings after the life tests described in Part 1.

The dent area densities were determined by processing surface images of a region 0.7mm x 0.9mm in the central part of the inner raceways obtained with an optical microscope. Measurement results are shown in Table 2. From a comparison between the results of A-3 and B-3 operated under a load of 6 860 N, it is obvious that the dent area densities differed greatly, even if the loading condition was the same. Similarly, the dent area densities varied between A-2 and B-2 operated under a load of 3 430 N. On the other hand, there was no clear difference in the dent area densities between A-1, B-2 and B-3 in which the lubricant film thickness was almost equal, in spite of a wide variation in load and operating time. It can be seen from these results that the degree of denting was not greatly affected by the load and depended largely on the film condition. The relationship between the central film thickness and the dent area density is illustrated in Fig. 2. As is realized from the figure, the dent area density tended to be proportional to the film thickness.

To simulate the effect of solid debris in lubricant on the life of roller bearings, Ai assumed that the number of dents formed in a unit area by debris particles of a certain size is determined by Eq. (1). In the equation, $h_m$ is the film thickness and $n_d$ is the number of debris particles in a unit volume of lubricant.

$$
S = h_m n_d
$$

Ai has shown the validity of the relationship between the number of debris particles in a unit volume $n_d$ (corresponds to debris concentration) and the number of dents $S$, by quoting the result of the experimental work conducted by Ville et al. in which the number of dents formed on the contact surface was measured for various operating times and debris concentrations. However, concerning the other relationship contained in Eq. (1), that is, the correlation between the film thickness $h_m$ and the number of dents $S$, experimental result has not been presented as evidence.

In the life tests described in Part 1, the dent area density on the raceway was almost proportional to the film thickness, as is demonstrated in Fig. 2. Because the dent area density is proportional to the number of dents, it was confirmed from the results shown in Fig. 2 that Ai’s hypothesis on the relationship between the film thickness and the number of dents is valid.
4. Changes in Dent Area Density during Life Tests

Then, to investigate the process of dent formation during the life tests, changes in the dent area density on the inner raceways with the passage of operating time were measured by interruptive tests under the same conditions as the life tests performed by using the same oil (series A in Part 1).

Changes in the dent area density under test conditions A-1, A-2 and A-3 are shown in Fig. 3. From the fact that the dent area densities had hardly increased after 1.5 h of operation under all operating conditions, it can be seen that the dents affecting bearing life had been formed during the initial 1.5 h.

An example of debris particles collected from the vicinity of the test bearings when 1.5 h had elapsed under condition of A-1 is shown in Fig. 4. Though debris the size of about 200 μm rolled to flat shape exists, most of the debris have been crushed to small sizes.

As is realized from Fig. 3, under conditions A-1 and A-2, the dent area densities dropped after the lapse of 1.5 h. The cause of this phenomenon is that the dents formed from the start of operation until the lapse of 1.5 h became smaller in appearance with repeated rolling contact thereafter11).

5. Changes in Debris Concentration during Life Tests

In test series A described in Part 1, bearing temperature varied depending on the load and thus the viscosity of lubricating oil in the test rig changed. To investigate the influence of such a viscosity change on the behavior of debris particles near the test bearings, the lubricating oils were sampled from the vicinity of the test bearings during operation under conditions as those of A-1 and A-3, and then the debris concentrations were measured.

The debris concentrations were measured at a time period from the start of operation until the lapse of 1.5 h. During that period, the operations were interrupted at each set time, and lubricating oils were extracted from the vicinity of the test bearings by the means shown in Fig. 5. After a dilution of extracted oils with a solvent, debris particles were collected by filtration. Then, from the mass of the extracted oil \( m_\text{p} \) and the mass of debris \( m_\text{d} \) in the extracted oil, the debris concentration \( c_\text{d} \) was calculated by the following equation.

\[
    c_\text{d} = \left( \frac{m_\text{d}}{m_\text{p}} \right) \times 100 \% \tag{2}
\]

Changes in the debris concentration are shown in Fig. 6. The measurements were carried out three times for each operating time in both operating conditions. Regardless of operating conditions, in the initial stage of operation, debris existed near the test bearings in the concentration close to the average level that is calculated from the mass of debris and the mass of lubricating oil introduced into the test rig. However, the debris settled thereafter and their concentrations ranged from one-third to one-fifth of the average level when 1.5 h had elapsed.

Measurements were performed under two conditions in which bearing temperatures varied significantly from each other, but a clear difference in the changes of the debris concentration was not found. This means that a change in oil viscosity due to a difference in bearing temperature did not greatly affect the behavior of debris near the test bearings. It is confirmed from these results that even if the same amount of debris exists near a bearing, the degree of denting varies depending on the lubricant film thickness differing with the bearing temperature.
Debris particles passed through the contact have been deformed into flaky shapes or crushed into small particles as shown in Fig. 4, and consequently, the ability of dent formation has been lost. Therefore in the case of performing life tests by using a test rig in which the precipitation of debris does not occur, it can be predicted that a result similar to those of the life tests described in Part 1 is obtained because the amount of damaging particles decreases at the initial stage of operation. Practically, life test results obtained by Tanaka et al.\textsuperscript{12)} by using a test rig which excluded the precipitation of debris, because of small quantity of enclosing oil, showed a similar tendency to those observed in the results obtained in test series A discussed in Part 1. Therefore, it can be concluded that under conditions in which the precipitation of debris does not occur, the film thickness effect on bearing life is similar to that in the life tests discussed in Part 1.

6. Discussion

From the measurement results of the dent area density and the debris concentration, it was confirmed that the degree of denting changes with the lubricant film condition even if the same amount of debris exists near the bearing. As the reason for this phenomenon, it is considered that, in the case of large film thickness, a large volume of lubricating oil enters the contact and consequently a larger amount of debris is drawn into the contact.

The lubricant film thickness in test A-1 was approximately two times larger than that in test A-3 as shown in Table 2. Therefore, in test A-1, the volume of lubricating oil passing through an area in the contact between ball and the inner race at a certain period was almost two times larger than that in test A-3. On the other hand, there was no difference in debris concentrations near the test bearings under both conditions as shown in Fig. 6. It is inferred from these facts that, in test A-1, the amount of debris particles entering the contact together with lubricating oil was about two times larger than that in test A-3, as a result, the number of dents formed on the raceway was nearly twice larger.

7. Conclusions

1) By measuring the area densities of dents formed on the inner raceways during the life tests under contaminated lubrication, it was found that the degree of denting depends largely on the lubricant film condition and is not greatly affected by the load.

2) The dent area density on the raceway tended to be proportional to the lubricant film thickness. It was confirmed from this result that the relationship between film thickness and the number of dents, which was assumed by Ai, is valid.
3) When 1.5 h had elapsed from the start of operation, most of the debris had been deformed into flaky shapes or crushed into small particles. Therefore, new dents hardly formed thereafter. It follows from this circumstance that, under such conditions as those of the life tests discussed in Part 1 in which lubricating oil contains debris at the start of operation, bearing life is dominated by the dents formed in the initial stage of operation.

References